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Low carbon heating and cooling by combining various technologies with Aquifer Thermal Energy Storage

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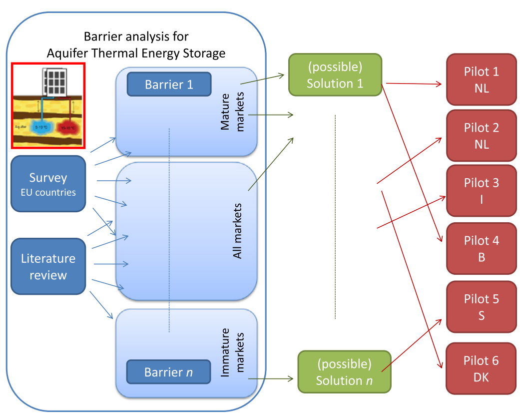
HIGHLIGHTS

- Barriers for ATES application in Europe are identified and categorized.
- Solutions to overcome barriers are identified, successfully implemented and evaluated in 6 pilot studies.
- Combining ATES with other technologies (e.g. soil remediation and PVT) help to overcome barriers.
- ATES systems have now proven to be applicable under strongly varying conditions in different European countries.

GRAPHICAL ABSTRACT



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ABSTRACT

A transition to a low carbon energy system is needed to respond to global challenge of climate change mitigation. Aquifer Thermal Energy Storage (ATES) is a technology with worldwide potential to provide sustainable space heating and cooling by (seasonal) storage and recovery of heat in the subsurface. However, adoption of ATES varies strongly across Europe, because of both technical as well as organizational barriers, e.g. differences in climatic and subsurface conditions and legislation respectively. After identification of all these barriers in a Climate-KIC research project, six ATES pilot systems have been installed in five different EU-countries aiming to show how such barriers can be overcome. This paper presents the results of the barrier analysis and of the pilot plants. The barriers are categorized in general barriers, and barriers for mature and immature markets. Two pilots show how ATES can be successfully used to re-develop contaminated sites by combining ATES with soil remediation. Two other pilots show the added value of ATES because its storage capacity enables the utilization of solar heat in

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Heating and cooling
Pilot plant
Technological innovation
Remediation
Photovoltaic-thermal module
Water scarcity

combination with solar power production. Finally, two pilots are realized in countries with legal barriers where ATES systems have not previously been applied at all.

1. Introduction

1.1. Aquifer Thermal Energy Storage contributes to greenhouse gas savings

Reduction of greenhouse gas (GHG) emissions is one of the main global challenges (UN, 2015). Large scale adoption of sustainable energy technologies is needed to reduce the use of fossil fuels. The global demand for heating and cooling in the built environment accounts for about 40% of the total primary energy consumption (IEA, 2009, RHC, 2013). Therefore, the development and world wide application of renewable energy technologies in the field of buildings heating and cooling would contribute significantly to GHG emission reduction (Rosiek and Batlles, 2013; Moretti et al., 2013; IEA, 2007). Because many urban areas are in moderate climates with a distinct heating and cooling season (Bloemendal et al., 2015), a seasonal storage is very efficient for combined heating and cooling systems (Tomasetta et al., 2015; Epting et al., 2017). As a result, heat storage in easily accessible shallow (<300 m of depth) subsurface has received interest since the 1970's (Sanner, 2001). In particular, Aquifer Thermal Energy Storage (ATES) is a versatile type of seasonal thermal energy storage for larger buildings because it is relatively cheap and easy to achieve large capacities.

1.2. ATES adoption is diverse

Potential for ATES is present in many locations around the world (Bloemendal et al., 2015) and various ATES systems have been reported in operation for heating and cooling supply (Gao et al., 2017; Bertani, 2005). However, ATES developments were up-to-now mainly carried out in the Netherlands, while this technology is now also picked up in other countries, such as Belgium, Denmark, Germany, Sweden and the US (Lee, 2010; Fleuchaus et al., 2018). Despite this experience and developments in recent decades, ATES technology still requires further development, and its market is rather immature in many countries. Building systems, geohydrological conditions, legislation and societal perseverance vary strongly from country to country. Therefore, barriers that limit adoption may also be various and diverse. In order to significantly increase adoption, such barriers must be better identified and addressed. The goal of this research is A) to identify and categorize barriers for ATES adoption across Europe and B) identify and test possible solutions to overcome these barriers.

This paper presents the results of a barrier analysis for ATES implementation in Europe in Section 3. Novel technological developments and scientific insights to overcome these barriers, are then used to transform the identified barriers to opportunities for development of ATES in Section 4. Some of the solutions are implemented in pilot sites which are presented and discussed in Section 4 and supplementary material.

The activities are carried out within the *Europe-wide use of sustainable energy from aquifers* project, which aims at improving and developing ATES technology via innovation. A description of the project goals and partners is given in the supplementary material.

2. Methods and materials

2.1. ATES characteristics and working principle

Seasonal underground thermal energy storage systems are often referred to as ground source heat pumps, and are essentially a combination of a heat pump and a system for exchanging heat with the subsurface (Sarbu and Sebarchievici, 2014; Omer, 2008). Usually two different main types of systems are distinguished:

1. Borehole thermal energy storage (BTES): a series of U-shaped pipes which carry a thermal working fluid that transfer heat to the surrounding soil via conduction. Usually applied in smaller buildings and single family homes.
2. Aquifer Thermal Energy Storage (ATES): a system using groundwater from two or more groundwater wells. Suitable for larger utility buildings like offices, hotels and hospitals.

ATES systems are more efficient and enable storage of larger quantities of heat because groundwater is used as a carrier for the heat (Fig. 1). Cooling is provided in summer by using groundwater from the cold well; cooling down the building warms up the groundwater to about 15–18 °C, which is then stored in the warm well. During winter, groundwater is extracted from the warm well, and together with a heat pump, provides heating to the associated building. The same groundwater is simultaneously reinjected at around 5–8 °C in the cold well. Because ATES provides both heating and cooling, it is most suitable for buildings with both a cooling and heating demand. Moreover, ATES requires the presence of an aquifer. Therefore, the two most important environmental preconditions for applicability of ATES are presence of aquifers and a heating and cooling season (Bloemendal et al., 2015).

2.2. Barriers identification

Literature study and a survey are the methods used to identify the barriers for development of ATES systems in order to obtain a representative geographical coverage. Following the conclusions of the literature review (Haehnlein et al., 2010; Regeocities, 2014; Monti et al., 2012; Forsen et al., 2008; Koenders, 2015), a questionnaire is set-up and sent out as a survey to partners across Europe with local knowledge and experience in the field (questionnaire questions are included in the supplementary material). Local experts received a survey and a total of 21 people returned the questionnaire, their answers were integrated by additional interviews. The countries involved with the survey are The Netherlands, Belgium, Italy, Spain, Germany and the United Kingdom (of which the latter two did not host a pilot plant in the subsequent project). Barriers in Eastern and Northern European countries were also available in the literature (Haehnlein et al., 2010; Regeocities, 2014; Monti et al., 2012; Forsen et al., 2008). Therefore, the barriers identified in this paper can overall be considered representative for the whole of Europe, although more focus has been paid to Western and Southern Europe. Consequently, some specific local barrier in North or Eastern Europe may be missing.

2.3. Identification and testing of solutions

Solutions for most barriers are trivial and are identified following logical reasoning, solutions used in other countries/fields, or are provided already in literature.

Basically, each barrier will limit ATES adoption to some extent. It is, however, not feasible to tackle all barriers simultaneously and it is also often difficult to identify which barrier limits ATES adoption the most, as often multiple barriers limit ATES adoption. Therefore, local partners have found suitable sites to test one of the proposed solutions to a

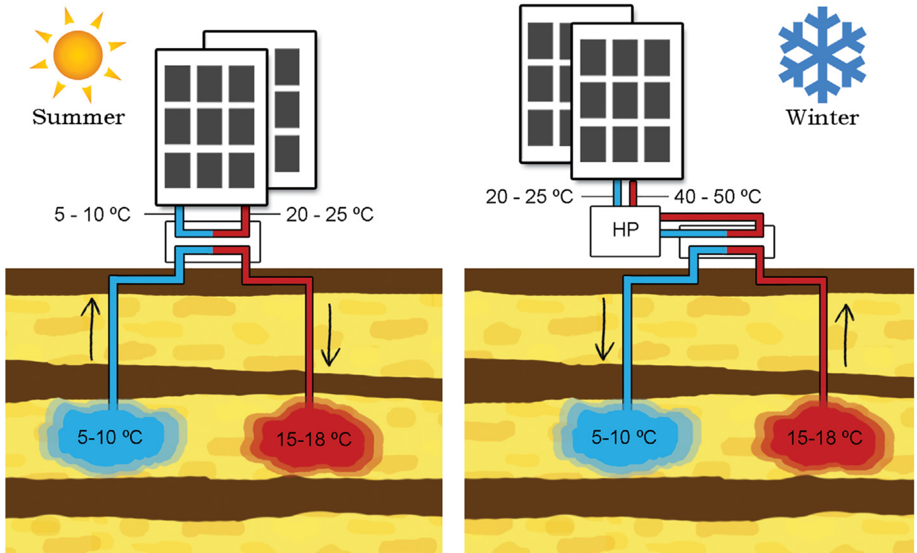

Fig. 1. Illustration of the basic working principle of an ATES system. Left: in direct cooling mode while storing heat for winter. Right: in heating mode supported by a heat pump while storing cooling capacity for summer.

barrier in a pilot project. The technological solutions selected for pilots are the ones needed for the specific barrier/solution in the project sites. The pilots are installed and monitored; results of installation processes are described in this paper, and where possible the performance is evaluated.

The pilot sites, the partners involved and the technology added to the ATES system are diverse; therefore, it was not possible to identify a uniform assessment framework. Also not yet each project has data available to evaluate. The assessment methods that were used for assessing the pilot results are straightforward and well documented in literature which are introduced in each pilot section in the supplementary material.

3. Results barriers and solution identification for ATES development and adoption

3.1. Barriers identification results and analysis

3.1.1. Literature review on ATES barriers

The worldwide ATES development has been well described by Fleuchaus et al. (2018): they show that the main developments of ATES are present in the Netherlands. Most research on these systems are carried out by the Dutch, although also several reviews have been published on ATES systems in other countries (e.g. Tomasetta et al., 2015; Gao et al., 2017; Haehnlein et al., 2010; Rogen et al., 2015; Zhou et al., 2015). The main topics addressed are reported below:

– Legislation: In earlier work Hahnlein et al. made an inventory of ATES legislation (Haehnlein et al., 2010). Legislation varies from country to country, all using the precautionary principle as a basis. Countries where groundwater is scarce are more restrictive than others. This study goes into more detail on identifying which sets of rules either foster or limit ATES adoption.
– Groundwater quality: Two research programs on the effects of ATES on groundwater quality were landmark studies (Koenders, 2015; Bonte, 2015), concluding that low temperature ATES systems like the ones discussed in this paper have negligible effects on groundwater quality. Nevertheless, still many research questions remain on how larger temperature changes (>30 °C) affect groundwater quality and how to deal with the changes in physical properties of the groundwater around ATES wells. ATES wells placed in contaminated aquifers cause spreading and dilution of the contamination (Phernambucq, 2015). Ni et al. (2014, 2015) carried out theoretical work on how ATES and decontamination can be combined. This paper starts from their findings to translate these into practice.
– System design: The Dutch industry organization developed design standards, mainly focusing on avoiding well clogging and integration of the ATES wells and heat pump in the building system (NVOE, 2006). Earlier and recent work of Douhty et al. (1982), Sommer et al. (2015) and Bloemendal and Hartog (2018) provided a theoretical basis for optimal use of subsurface space and how to deal with specific geohydrological conditions (e.g. groundwater flow, high density use of ATES, heterogeneity). This paper takes further steps in the integration with the buildings system and overall performance of the ATES system.
– ATES in practice: The permitted capacity of individual ATES systems in the Netherlands ranges up to 5,000,000 m^3/year, such large systems have multiple well doublets. However, the majority (~70%) of the systems are even smaller than 500,000 m^3/year, with only one or two well doublets (Bloemendal and Hartog, 2018). Depending on aquifer thickness, the associated thermal radius of influence around ATES wells ranges from 20 to about 150 m (Bloemendal and Hartog, 2018). Review and evaluation of the performance of individual ATES was until recently not required (Schultz van Haegen, 2013). The limited number of studies (Willemsen, 2016; Haaglanden, 2017) that have been carried out indicate that in general ATES systems save energy but not yet to their full potential; so, their operation can be optimized.

3.1.2. Survey results

The obtained results are fully described and available in the pathfinder project report (Hoekstra et al., 2015).

3.1.2.1. Quality level of ATES systems and suppliers. The quality level of ATES systems installation and suppliers was identified as a main general barrier. Design, construction and operation by unqualified parties results in poor performance of ATES systems. Poor quality of the work and/or material can generate malfunctions during operation and/or poor energy efficiency, affecting (potential) users' trust in the technology and eventually resulting in a negative reputation for ATES systems.

3.1.2.2. Knowledge and skills divided between consulting and contracting companies and operational staff. High efficiency of ATES systems requires

not only a good design of the entire system, but most importantly appropriate operational control and management: the lack of the latter can cause poor ATES systems performance, despite proper design and construction. Different types of expertise are required to build and operate an ATES system, currently separated in a fragmented and often complex supply chain, e.g. construction engineers for the energy demand, specialized drilling contractors for the wells, geologists for hydrogeological characterization of the site, Heating Ventilation and Air Conditioning (HVAC) installers for heat pump, distribution and peak facilities. Such a fragmented supply chain requires a significant effort to obtain an integrated and robust ATES system that will function properly once in operation. Therefore, inadequate cooperation between different companies in an early stage, or the absence of a unique market player taking control and responsibility for design, construction and operational phase, is a barrier for optimal design and operational performance of ATES systems.

3.1.2.3. Mutual interaction between ATES systems. The demand for ATES is usually concentrated in urban areas with high building density. In cities, the demand for ATES may therefore easily exceed the available capacity of the subsurface: this may represent a natural threshold limit for ATES implementation. This aspect is considered to be the most important barrier for ATES adoption in countries with a mature ATES market. The issue of mutual interaction between ATES systems also requires proper management and planning. An important policy parameter for the planning of ATES systems is the minimum distance between individual wells. This is typically defined using the thermal radius (R_{th}) of the wells (Bloemendal and Hartog, 2018); in theory, this distance could be reduced significantly in an aquifer without ambient flow (Bloemendal et al., 2014; Sommer et al., 2015). Several studies show that a trade-off can be found between optimal use of the subsurface for total energy savings on one hand and individual ATES well efficiency on the other (Jaxa-Rozen et al., 2015; Bloemendal et al., 2018). Additionally, it is not widely known that mutual interaction between ATES wells in a dense, well-organized ATES well-field improves, rather than diminishes, the overall thermal performance of these systems because combining wells of the same type increases their efficiency a lot (Bloemendal et al., 2018; Sommer et al., 2015). The reluctance of groundwater management policy makers to allow a dense network of ATES systems has a negative impact on individual efficiency and overall energy savings. Another cause of this barrier is the lack of evaluation of the actual status of the groundwater system, which jeopardizes long term usability of the aquifer. Groundwater extraction and infiltration are monitored but their resulting thermal influence is not evaluated. Dutch practice shows that actual pumped volumes are much smaller compared to the design values, on average 40% of the permitted capacity is used. Ambient groundwater flow can affect both the individual ATES systems as well as downstream installed ATES systems. At ambient groundwater flow velocities <25 m/year this effect is negligible, while at higher groundwater flow velocities design changes are needed to maintain overall efficiency and avoid negative interaction (Bloemendal and Hartog, 2018; Bloemendal et al., 2018; Bloemendal and Olsthoom, 2018).

3.1.2.4. Interaction with other subsurface functions. Next to interacting with each other, ATES systems also interact with other subsurface space use. Because of the shallow infrastructure (power cables, drinking water pipes, internet, sewerage, tunnels, parking garages, etc.) it is often difficult to find a location to install an ATES well in the shallow subsurface in densely built urban areas. This is, however, only a barrier during construction activities.

In the storage aquifer, interactions between ATES and/or other subsurface functions are dynamic and ongoing during the life span of ATES systems. The main interactions occur with groundwater production sites for industrial, agricultural use and for drinking water production as well as with remediation and management of contaminated groundwater. The potential conflict of ATES with groundwater production can be stronger in areas with water scarcity. Drinking water production and agricultural use are, however, hardly ever in conflict with ATES, because A) these groundwater extractions are (with some exceptions (Bonte et al., 2013)) usually located outside urban areas where ATES is applied, and B) the water quality change of the groundwater by ATES has a very limited effect on the groundwater quality (Bonte, 2015). Thanks to spatial planning, industries requiring large quantities of groundwater are hardly ever near areas where demand for ATES systems is high. On the other side, interaction between ATES and groundwater contamination are more likely to occur in urban areas with shallow aquifers. Two main problems need to be considered when applying ATES in or near a groundwater contaminated site. The first one is the legislation: due to application of precautionary principles it is often not allowed to affect/influence the pollution through ATES systems. The second one is a technical drawback: due to dilution and mixing of contaminated groundwater chemical and biological reactions with precipitation products may occur in or near the wells, resulting in clogging of the groundwater wells. However, with adapted system design (e.g. location and type of well, addition of other material for well completion) and an adapted maintenance program (e.g. more frequent backwash with chemicals), these problems can be avoided. Next to other subsurface functions, ATES may also interact with BTES systems (technology frequently applied in urban areas), nevertheless the mutual effect of ATES and BTES systems is usually limited (Drijver et al., 2013).

3.1.2.5. Lack of knowledge, experience and public awareness. Lack of experience and awareness of both ATES technology and heat pumps is an important factor limiting ATES adoption in new markets. Compared to gas boilers, HVAC installers consider heat pumps as "difficult" technology. Most of the smaller HVAC contractors are usually micro or small enterprises with limited awareness about the possibilities and recent advances of heat pumps and a lack of knowledge about subsurface characteristics and ATES potential. Therefore, ATES will not be offered as an option to clients of these companies, which are most often small buildings (around 100 kW or 10,000 m^2 floor space and smaller (Agterberg, 2016)). Despite the limited size of the single plant installation of such buildings, their large number (Agterberg, 2016) makes that the total energy saving potential is enormous, thus this barrier is of major importance.

Public awareness may also be an important driver or limitation for ATES adoption. Although outside of the scope of this research, the public opinion on ATES can become strongly affected by negative reputation originating from project failures. In some cases, the negative public opinion has even been caused by another type of geothermal technology than ATES (Fleuchaus and Blum, 2017; Grimm et al., 2014), so, despite numerous efficiently running projects, one failure can have large consequences for the public opinion.

3.1.2.6. Lack of adequate legislation. Legislation for ATES varies from country to country. In countries where ATES is widely applied, specific legislation has been designed or modified to regulate and/or stimulate the technology, while in countries with low application of ATES, legislation is lacking or poorly substantiated (Haehnlein et al., 2010). In general, legislation for ATES permitting is also complex and not uniform across countries, often leading to long, laborious and uncertain permitting procedures. In some countries (e.g. Spain and Italy) the responsible authorities involved for issuing ATES permits are many and vary as a consequence of administrative divisions, resulting in the fact that there are different procedures and assessment criteria to follow to obtain a permit, depending on where an ATES project is located. In addition to that, lack of knowledge at permitting authorities about ATES systems and their negligible environmental impacts may cause an additional barrier.

3.1.2.7. Financial aspects. In Southern and Eastern European countries one of the main barriers for application of ATES is uncertainty on their economic sustainability. The required initial investment is a barrier for implementing ATES systems: the combination of heat pump and groundwater wells require a significant investment compared to conventional HVAC systems. The uncertainty or lack of knowledge on the potential savings, the competition from cheap fossil fuels and the overall conditions of economic recession may prevent operators from investing in ATES.

No specific financial subsidies for ATES systems realization were found in the countries involved in the E-USE(aq) project survey (Hoekstra et al., 2015). Nevertheless, in most countries an ATES system installation can usually benefit from one or more subsidies financing heat pumps installation, energy efficiency actions (white certificates), renewable energy production (green certificates), buildings renovation etc., but the impact of such subsidies is generally limited to a marginal reduction of ATES system payback time.

3.1.2.8. Unfamiliarity with the subsurface and its characteristics. To evaluate the applicability of ATES systems, to ensure a proper design and most importantly to avoid malfunctions during operations, adequate technical knowledge of the local geo-hydrological characteristics is necessary. The main issues related to the geo-hydrologic conditions are: aquifer depth and hydraulic conductivity, well clogging and insufficient well capacity.

3.1.2.9. Energy balance. To sustain an ATES system, the thermal energy stored in the aquifer must be of comparable magnitude to the retrieved amount, to avoid short or long term temperature fluctuations. This implies that, ideally, the heating and cooling demand from the building associated to the ATES system should be equal. This is both a technical as well as a legal issue; it affects the individual operation of each ATES system (technical issue), but due to potential imbalance between warm or cold wells, this may also affect neighboring ATES systems (legal issue). Alternatively, the system performance can be optimized by storing extra heat or cooling capacity from other (sustainable) sources such as solar radiation (Paksoy et al., 2000; Kastner et al., 2017; Ghaebi et al., 2014.

3.1.3. Conclusions about barriers identification and analysis

The identified barriers strongly relate to the level of market maturity. For instance, interaction between ATES systems is a clear mature market problem because that will only occur when many systems are built in one area, while lack of knowledge and awareness preventing market development is a typical immature market problem. Therefore, the barriers can be categorized to general, immature and mature market barriers, resulting in:

1. General barriers: quality levels of ATES system, legislative barriers, separation of knowledge and skills in the supply chain for ATES implementation and realization, uncertainty about ATES impact on groundwater characteristics, energy balance between heating and cooling demand.
2. Mature market barriers: mutual interaction among ATES systems, interaction with polluted groundwater.
3. Novel market barriers: public awareness, lack of knowledge, large initial investments, unfamiliarity with the underground and its characteristics.

3.2. Solutions to overcome local barriers

Following the identification of technological and non-technological barriers, possible solutions are identified in order to overcome these barriers while stimulating, facilitating or regulating the ATES market.

1. Solutions for the general barriers.

- Implement quality guidelines and certification to safeguard skills of personnel and the quality of ATES construction work and operation.
- Monitor and evaluate the temperature distribution in the subsurface, e.g. by a monitoring network and/or numerical computational evaluation.
- Use a general/cross-sector assessment framework to make an informed decision about allowing ATES, in particular in or near a contaminated zone and/or areas with groundwater stress.
- Ensure that regulations are similar within a single country. Possibly also try to regulate and facilitate ATES application through a European framework directive.
- Develop an assessment framework to evaluate the overall performance and associated level of energy savings as a combination of i) individual ATES system performance and ii) optimal and sustainable subsurface space use.

2. Solutions for mature markets barriers:

- Use flexible ATES permits that allow increasing or decreasing the permitted capacity according to actual use. This then allows the spatial claims in the subsurface to be adapted over time, and safeguards optimal and sustainable use of the subsurface.
- Improve ATES systems control systems to optimize long term thermal efficiency for both individual systems as well as for the overall efficiency of aquifers densely occupied by ATES systems.
- Develop better technologies to enhance degradation of contaminants and to overcome the clogging problem related to the chemical reactions in areas with contamination.

3. Solutions for novel markets barriers:

- Stimulate ATES adoption rates to create awareness by initiating pilot projects, show cases and progressive building energy efficiency regulation.
- Stimulate ATES application by setting a high energy efficiency standard for new and/or renovation buildings by eliminating HVAC systems from the business case comparison.
- Provide detailed suitability maps for regions/countries, indicating specific characteristics which influence installation cost and/or operational requirement.
- Set up a scientific program to evaluate the environmental impacts of ATES systems in the European context, similarly like was already done in the Netherlands (Bertani, 2005; Bonte, 2015).
- The introduction of specific financial subsidies for the realization of ATES system, to strongly reduce payback time and lead to an increasing number of installations. Governments could also help by bridging the gap between the site or building owner, who has to make the investment, and the site user or tenant, who usually profits from lower energy bills (Hoekstra et al., 2015). Through tax deductions on the investments, paid for by increases on fossil energy taxes, installation of ATES becomes attractive for both parties. Such a tax arrangement would definitely stimulate the construction of more systems. But it is not necessarily the government that would need to take this action; commercial organizations could also encourage business with ATES systems (Hoekstra et al., 2015). For instance, banks can create comparable incentives by initiating agreements that are profitable for all parties.

4. Preliminary results from pilot sites

4.1. Description of pilot sites

In this section the results of three of the six pilot plants are discussed to give an indication of some of the obtained results. The supplementary material presents extensive descriptions and results of each pilot site.

In this work, different innovative solutions (summarized in Table 1) have been implemented in the six pilot plants to overcome the technological barriers to ATES implementation that are present in mature markets (The Netherlands), developing markets (Belgium, Denmark) and new potential markets (Spain, Italy). Pilot plants main characteristics are summarized in Table 2.

The non-technological barriers are also faced as the project consortium worked to build strong and cross-sectoral local partnerships. This is to guarantee a high level of skills and knowledge development and transfer, and to ensure an effective design and realization of the pilot plants. Furthermore, preliminary field tests are financially supported to increase the knowledge of groundwater characteristics (in particular, in non-Dutch pilots). The realization of robust monitoring systems is implemented in all pilot plants to effectively monitor not only the impacts of pilot plants' operation, but also to provide more guarantees to the public administrations. Finally, numerous publications, presentations and events created awareness and familiarity both at local as wells as at international level.

4.2. ATES at contaminated sites

In laboratory studies it was shown that the combination of ATES and bioremediation of chlorinated solvents leads to a >10-fold increase of the biodegradation rate compared to natural attenuation (Paksoy et al., 2000; Kastner et al., 2017). Evidence of this acceleration of bioremediation by ATES in plumes of chlorinated solvents contaminated groundwater would be a clear demonstration that contaminated groundwater could be treated with ATES. Bioremediation is tested at two different contaminated sites: in the aquifers of Utrecht (NL) and Birkerod (DK), with low and high concentrations of chlorinated solvents, respectively.

At the Utrecht Nieuw Welgelegen pilot site a mono-well ATES system has been operating for several years. The groundwater at the location of the Nieuw Welgelegen pilot is contaminated with chlorinated ethenes, mainly vinylchloride (VC), which exceed target concentrations set by the Dutch National Institute for Public Health and the Environment (RIVM).

The aim of the Utrecht pilot study was to stimulate bioremediation at the ATES system by bioaugmentation: inoculation with *Dehalococcoides bacteria* (DHC). For this a separate injection well and 3 monitoring wells were installed (see a scheme of the pilot plant in the supplementary material, Fig. C3). The main mechanisms for increased biodegradation are threefold. Firstly, and most importantly, by inoculation of DHC a high concentration of specific biomass, able to degrade chlorinated ethenes, will be present in the system which should enhance biodegradation at optimal environmental conditions. Secondly, elevated groundwater temperatures in the warm well, in comparison to ambient groundwater temperatures, will generally lead to higher biodegradation rates and higher biomass growth rates. Thirdly, the added biomass can function as an electron donor, leading to lowering of the redox conditions which promotes reductive dechlorination.

The bioaugmentation pilot study at Nieuw Welgelegen showed that injection of a large volume of bacteria (4 m^3 with 2×10^8 cells/mL) did not result in negative impacts such as well clogging and the ATES system operated normally. DNA measurements performed on soil and groundwater samples revealed that the introduced DHC bacteria attached to the soil matrix and migrated from the bioaugmentation injection well to the monitoring and ATES wells.

Table 2
Pilot plants main characteristics.

Parameter	Delft	Utrecht	Birkerod	Ham	Bologna	Nules
No. of production wells[a]	1 + 1	3 + 3	1 + 1	1 + 1	3 + 3	4
No. of monitoring wells	6	3	4	2	4	4
Wells' depth (m)	60–80	15–55	22–55	162.5	30	35
Max groundwater flowrate (m^3/h)	25	45	–	80	19.4	14.4
Max cooling power (kW)	30	–	–	1300	140	–
Max heating power (kW)	70	–	–	650	160	109
Annual cooling demand (MWh)	160	525	–	900	49	–
Annual heating demand (MWh)	160	475	–	863	170	288

[a] Extraction and injection wells.

Although VC concentrations are generally low (<10 μg/L), several observations indicate that biodegradation is occurring. These include (i) decreasing VC concentrations at the bioaugmentation injection well (Fig. 2), and (ii) the detection of ethylene during certain time measurements. According to the molar ratios for the conversion of VC, a reduction of 5 mg/L VC will produce 2.28 mg/L ethylene. This supports the field observations reported here, as VC concentrations were initially 2–6.6 mg/L, and ethylene was subsequently detected at 2.2–2.4 mg/L. Furthermore, redox conditions indicate that the reduction of VC is thermodynamically feasible.

The results of the Nieuw Welgelegen pilot study support earlier lab scale experiments where the effect of pumping by an ATES system on the distribution of DHC biomass was investigated (Ni et al., 2015). From this study it became clear that an increase of biomass over time accelerates the biodegradation of chlorinated ethenes and that the DHC could attach to the soil matrix.

The results showing decreasing VC concentrations over two summer seasons are promising as this provides a system design by which VOCl contaminations can be effectively biodegraded at relatively low cost, without any negative impacts on the ATES system.

4.3. Energy balance requirement: integration of PVT technology in ATES systems

Solar collectors are used to obtain extra heat to meet the energy balance requirement. Using both solar heat and power would even further improve the energetic and economic performance of ATES systems as ATES systems also need electricity to drive heat pumps. Since in many climates solar heat is abundant in summer, while heat demand is largest in winter, seasonal storage of heat in an ATES system would utilize the potential excess heat production during summer.

Hybrid photovoltaic-thermal (PV/T) solar panels are a smart solution to combine heat and electricity production from solar energy in one device (Bianchini et al., 2017). The integration of PV/T technology in ATES systems will be tested for the first time at industrial scale in

Table 1
Innovative solutions tested in each pilot plant.

Main barriers and solutions	Pilot sites					
	Delft (NL)	Utrecht (NL)	Birkerod (DK)	Ham (B)	Bologna (I)	Nules (ES)
1. Contaminated site: combine ATES with bioremediation.		X	X			
2. Optimize energy balance and sustainable power use of ATES: integration of PV/T with ATES	X			X		
3. Optimize energy balance with district heating					X	
4. Familiarity	X	X	X	X	X	X
5. Legislative barriers		X	X		X	X

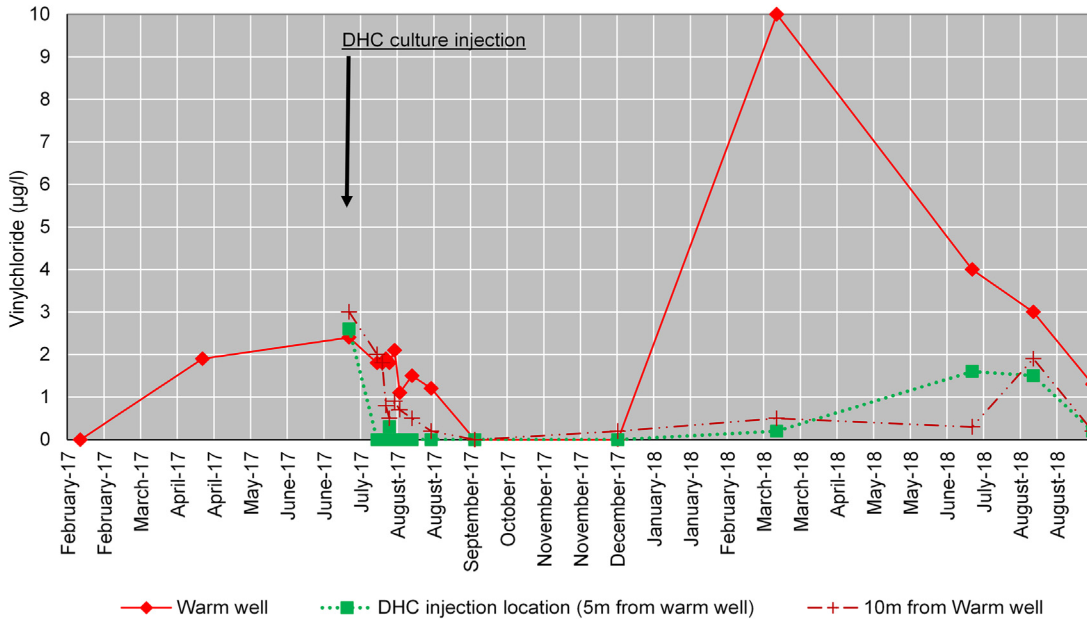

Fig. 2. Concentrations of vinylchloride in the ATES-3 warm well and bioaugmentation injection well. The time of the DHC inoculation is also shown. Summer operation: injection in shallow warm well, water flows from ATES-3 to the bioaugmentation well. Winter operation: extraction from warm well, injection in deep cold well. The VC concentrations increase during winter and decrease during summer due to the heterogeneous distribution of VC concentrations with depth (data not shown).

two pilots (Delft and Ham). In particular, in the Delft pilot an innovative PV/T system will be tested which is able to produce warm water at temperatures up to 70–80 °C.

The ATES system in Ham, Belgium, consists of two wells of about 160 m deep integrated with PVT solar panels. The data presented in Fig. 4 covers the first year of operation of the Belgian pilot (see spatial lay-out in the supplementary material). Fig. 4 shows that the storage of cold water worked very efficiently as the temperature extracted from the cold well also is around the injection temperature of 8 °C during the first part of the second cooling season and slowly increased to 11 °C at the end of August 2017. Fig. 4 also shows that after the initial period with cooling demand, the temperature in the warm well drops fast until it reaches the ambient temperature. This behavior is a result of the startup of the system at the end of the summer, resulting in limited storage of heat in the warm well. As a consequence, the temperature difference during heating operation is quite small and larger volumes from the warm well are necessary to provide the requested amount of heat, which then results in a depleted warm well already in January (thermal radius, $R_{th} = 0$). However, Fig. 4 also shows that at the end of this first year (August '17) the warm well is charged with heat: the infiltrated temperature in the warm well is on average 17 °C and the thermal radius is over 20 m. This indicates that during the 2017/2018 heating season the warm well will deliver warmer water, which means that a larger temperature difference will be realized and

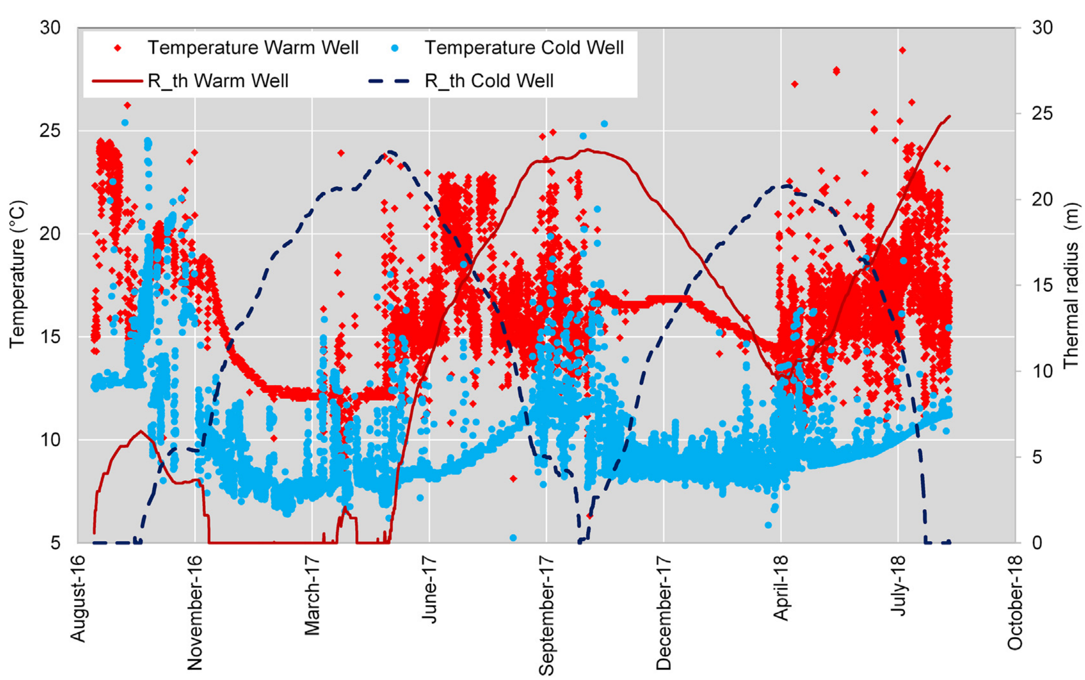

Fig. 3. Evolution of temperature at the warm and cold wells and calculated thermal radius of warm and cold well at Ham site.

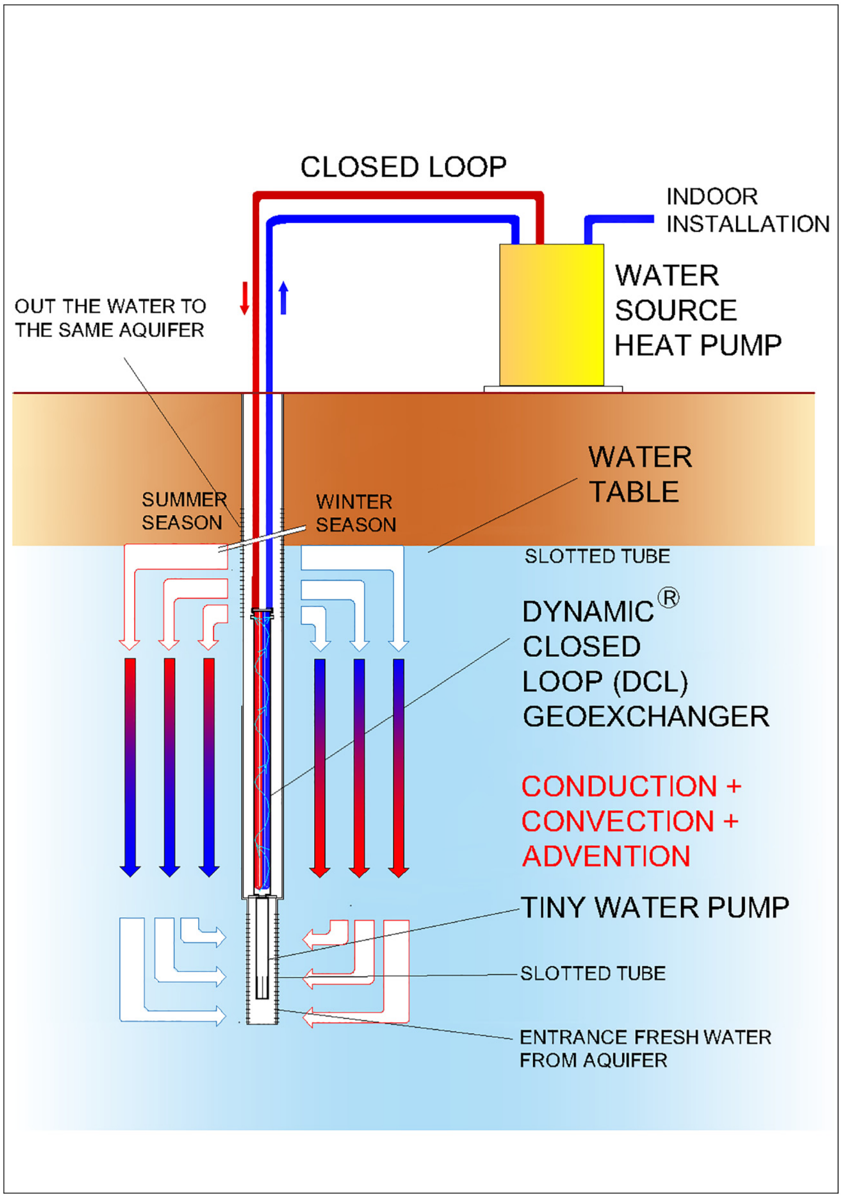

Fig. 4. Scheme showing how the Dynamic Closed Loop (DCL) probe works.

a smaller flow of water will provide the same amount of heat. Consequently, a smaller volume of cold water will be stored for each J of heat delivered. The cold well was not depleted at the end of the first year since the heating provided by the ATES was mainly realized by cooling down the cold well, and no heat was charged in the warm well.

The main findings of the energy monitoring during the first year of operation are that: i) PVT panels cover 13% of the domestic hot water demand during the monitored summer period, ii) despite being in summer, almost 50% of the heating demand was covered by the gas boiler due to an error in the HVAC control, which was adapted later, and iii) direct cooling represents only 7% of the cooling provided by the ATES. The latter is a problem as it has an important negative impact on the overall energy performance. The reason for this high amount of active cooling was an error of the HVAC system: it was found that the temperatures delivered by the ATES were more than sufficient for free cooling (see Fig. 3), but due to an error in the HVAC control the system was always put into active cooling mode. It is expected that in the second year of monitoring the full potential of the ATES in combination with PVT will be demonstrated, as it was found that after the modifications the system correctly switched to free cooling. These findings show how important it is to perform a thorough commissioning of the system, as mistakes in the programming of HVAC controls can have a serious negative impact on the performance of the systems.

4.4. Local legislation barrier overcome by dynamic closed loop probe system

In most regions of Spain groundwater pumped to the surface is treated as industrial wastewater, which then complicates permitting procedures. A solution to overcome this legal barrier is tested in the Spanish pilot plant, which is called Dynamic closed loop (DCL) probe. The DCL probe (Fig. 4) consists of a series of small diameter tubes through which the thermal carrier fluid is circulated, similar to the approach in regular BTES. These tubes are installed in a groundwater well with a screen at the bottom and top, when groundwater is pumped from the bottom to the top screen, the rate of heat exchange of the closed tubes increase strongly. This system is a hybrid solution, with the advantages of A) closed-loop system, since the groundwater is not extracted from the ground, avoiding legal barriers, and B) open-loop system, wherein the heat exchange is improved because there is no longer heat exchange by only conduction because of the groundwater flow

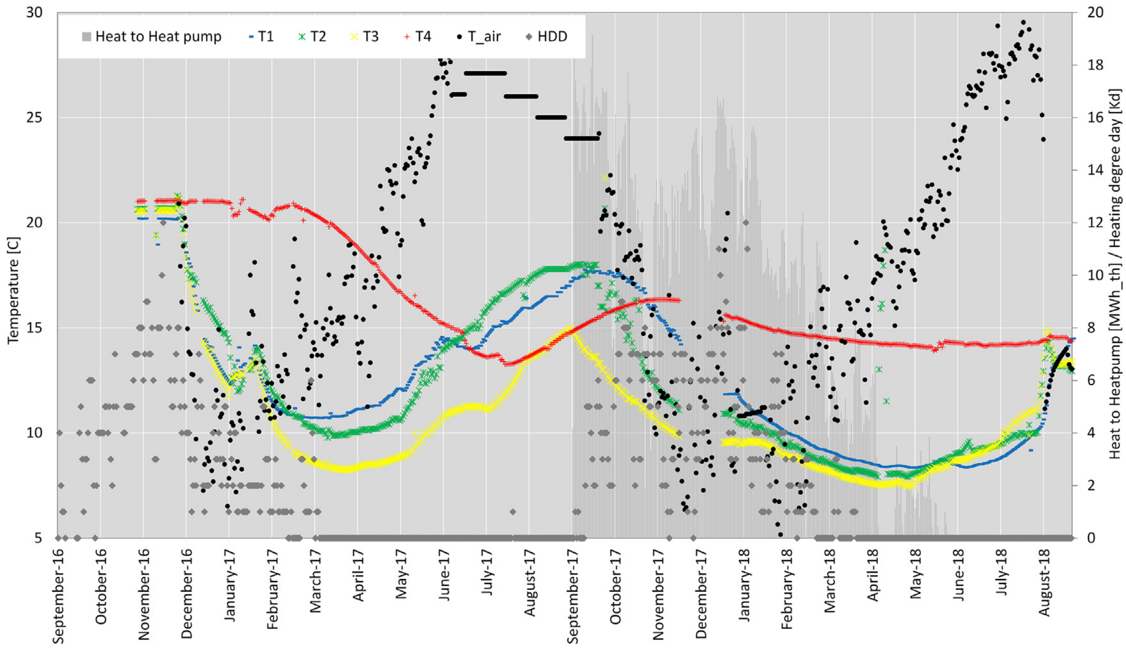

Fig. 5. Temperature and level variation of the four piezometers in one year; also ambient temperature variation is included (measured starting from 16th December 2016).

along the closed loop tubes. In this way the technology allows to obtain the permits, thus overcoming the legislative Spanish barrier regarding stringent limitation to water extraction for energy purpose. In the Netherlands mono-well systems are often equipped with a downhole heat exchanger, so groundwater flowing from one screen to the other does not leave the well. Such a construction also prevents groundwater from coming to the surface, and may be an alternative solution for the specific Spanish legislation.

A geothermal heat pump system with four Dynamic closed loop probes (DCL) probes have been installed in Nules (Spain) to keep the water temperature of a swimming-pool at 28 °C. The Spanish pilot plant is in operation since the end of 2016. The DCL probes working data have been registered on a weekly basis, the temperature and water depth variation in the groundwater has been monitored in the three piezometers around the DCL probes and in the fourth piezometer placed at a certain distance from the DCL probes, in the thermal plume direction (see Fig. C7 in the supplementary material for spatial layout).

Fig. 5 shows the temperature variation of the piezometers, together with outside air temperature, the heating degree days and the total amount of heat that was transferred from the subsurface to the heat pump (the latter is only available from September 2017 onwards). Monitoring locations 1, 2 and 3 are in between the 4 DCL probes so their temperature response is well aligned with the moment the heat pump starts operating, September 2017 onwards. The temperature response in the downstream monitoring location (T4) has a delayed response as the cold plume arrived in March 17 and November 2017, also recovering of the temperature lags behind from the moment heat extraction stops. More years of operation should confirm sufficient recovery of the groundwater temperature after each winter.

Several groundwater samples have been analyzed to evaluate the impact of the temperature change on groundwater quality. No considerable changes have been detected, with the exception of the chloride concentration increase in the summer season, which is due to the more saline groundwater that is pumped from the deeper to the shallow screen. Further monitoring is still on going to evaluate the impact of DCL probes in the mid-to-long term on chlorides, nitrates, nitrites and sulfates. Finally, the overall energy efficiency analysis shows a yearly decrease in natural gas consumption of about 60%.

5. Discussion and conclusions

The use of aquifers for thermal energy storage has large potential in Europe and can lead to relevant benefits from the environmental and economic points of view. Nevertheless, still many barriers need to be tackled to significantly increase ATES adoption across Europe. The "Europe-wide use of sustainable energy from aquifers" project has initiated six pilot sites to show how to overcome some of the barriers that were identified by literature search and by a specific survey. The identified technological and non-technological barriers varied with the level of ATES market maturity:

1. General barriers: quality levels of ATES system, legislative barriers, separation of knowledge and skills in the supply chain for ATES implementation and realization, uncertainty about ATES impact on groundwater characteristics.
2. Mature market barriers: interference between ATES systems, interference with polluted groundwater.
3. Novel market barriers: public awareness, lack of knowledge, large initial investments, unfamiliarity with the underground and its characteristics.

The design and realization of six pilot plants in five European countries characterized by different ATES system diffusion, legislation, subsurface characteristics and climate (The Netherlands, Belgium, Denmark, Spain and Italy characterized by different ATES system diffusion, legislation, subsurface characteristics and climate) is a relevant step forward for ATES development in these countries and shows how some of the above mentioned barriers can be addressed.

Next to providing a clear overview on the barriers and possible solutions, the main contribution of this research is to show that barriers for ATES adoption can be overcome in practice. In most of the pilot cases it was shown that these barriers are overcome by combining ATES with other (renewable energy or groundwater treatment) technologies, leading to mutual benefits.

The solutions proposed and implemented in the presented pilot sites are highly replicable in similar situations in these and other countries, as they can be easily adapted to local conditions.

5.1. Discussion & limitations

First results from the pilot sites prove that the implemented technological solutions showed benefits from techno-economic and environmental perspectives (e.g. solar energy harvesting in Belgium and The Netherlands and heating delivered to the swimming pool with ATES in Spain without groundwater withdrawal). It is demonstrated that ATES systems can be applied under strongly varying conditions in different European countries and through different innovative technological solutions. To further strengthen these results, continued investigations and long term monitoring and evaluation of projects is needed, also including an economic perspective. This study was carried out within a limited number of countries; although both our literature review and pilot results show many similarities among barriers across the world, specific solutions may not be appropriate or feasible in some countries. For Europe-wide adoption of ATES much more attention to the technology still has to be attracted.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.01.135.

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